Moisture Sorption Isotherms for Bacon Slices

R. P. KONSTANCE, J. C. CRAIG, JR., and C. C. PANZER

ABSTRACT

There is substantial evidence that controlled dehydration of bacon products to a water activity of 0.92 or below should allow control of spore outgrowth and toxin production by *Clostridium botulinum* and permit reduction of added nitrite levels. This study presents sorption data necessary for the development of a practical dehydration technique for bacon. Variations in fat/lean ratio, storage temperature, sorption mode, and drying method result in changes to the moisture sorption isotherms. Of these parameters only fat/lean variability of bacon significantly affects the isotherms at water activity levels above 0.90. Empirical equations for the isotherms were derived and used to establish differences in the isotherms due to variation in the parameters studied.

INTRODUCTION

THE STATE OF WATER in foods has a direct effect on their quality and stability through its effects on chemical (Labuza, 1980) and enzymatic (Rockland, 1957; Acker, 1963) reactions. For this reason, control of water activity (a_w) has been an area of concentrated research. In traditional processing, a_w is reduced by freezing, addition of ionic or nonionic solutes, or drying. In bacon, although curing additives (salt, sugars, nitrite, spices) reduce a_w, *Clostridium botulinum* spore outgrowth is retarded principally through the action of sodium nitrite (Benedict, 1980). Recent proposed reductions in the level of added sodium nitrite to reduce the formation of carcinogenic nitrosamines in fried bacon products have produced concern about possible botulism outbreaks and led to research on alternative methods of preservation. One such alternative is to reduce the a_w of bacon by drying. An a_w reduction to 0.92 or lower presumably provides ample assurance that the outgrowth and toxin production of *Clostridium botulinum* will be inhibited (Anon, 1975).

Ongoing studies of low-temperature air drying of bacon slices indicate that dehydration to an $a_w = 0.92$ can be accomplished with no substantial change in product quality. The extent of the moisture reduction required is, however, dependent on a number of processing and storage parameters. The purpose of this study is to identify the role of these parameters in the sorption isotherms of bacon slices. Leistner and Rödel (1975) indicated that fat content indirectly influences a_w. In bacon products where fat content is substantial and highly variable, it is important to fully understand the role that changes in composition play on product stability. Wolf et al. (1973) showed that changes in storage temperature markedly affected the isotherms for raw chicken. Kapsalis (1980) discussed hysteresis as related to food products and Wolf et al. (1972) showed the effects of sorption mode on the isotherms for freeze-dried pork, apples, and rice. The sorption data presented for bacon slices include the effects of these parameters as well as drying method over an a_w range 0.10–0.96. Using this range of data, empirical equations were developed that predict the major portion of the isotherm. The empirical relationships were then used to determine statistical differences due to the parameters under investigation. These relationships also provide a meaningful tool for the development and comparison of isotherms for other salted cured meats.

Authors Konstance, Panzer, and Craig are with the USDA-ARS, Eastern Regional Research Center, 600 E. Mermaid Lane, Philadelphia, PA 19118.

MATERIALS & METHODS

BACON USED in this study was purchased locally as fully processed slabs. The bacon was sliced to about a 0.3-cm thickness, with slice order being maintained. Alternate slices were analyzed for fat content, and the others were dried and used for a_w and moisture determinations. The average fat content of the two surrounding slices was used as the fat estimate of the dried slice. Chopped rather than ground samples were used for the fat analyses because fat loss due to grinding was found to be significant. Bacon pieces, about 3-cm square, were soaked in petroleum ether for 18 hr and then extracted for 5 hr by Soxhlet extraction.

Bacon slices used for the desorption studies were either freeze-, air-, or microwave-dried. Samples to be freeze-dried were frozen at −18°C and dried in a Virtis Model 10-145 MR-BA. A desiccated-air dryer (CGS Laboratory) was used for air-drying bacon. Samples were dried at 10°C dry-bulb temperature and 10% relative humidity with air velocity at 360 ft/min. The microwave unit was a Cober continuous dryer with through-flow heated air at 38°C. Piece temperature was monitored, and severe overheating was prevented through intermittent application of the 2-kw power.

Water activity measurements for the desorption isotherms were determined with a hygrometer/sensor system from the American Instrument Co. (Model LI 53054). A set of eight narrow-range sensors, each with a 15% RH span, were used. After each sample measurement, the sensors were calibrated against various saturated salt solutions of known relative humidity. Water activity values for these solutions were reported by Greenspan (1977). Sensor repeatability was ±1.7% RH, which agrees with the findings of Stoloff (1978) for this equipment.

Sample holders for the a_w measurements were ½-pint mason jars with lid assemblies modified for sensor attachment. These mason jars were used to minimize headspace volume and decrease equilibration time. Samples were maintained at constant temperature (±0.1°C).

Bacon slices used for the adsorption tests were freeze-dried until completely dry, placed in vacuum desiccators, and allowed to equilibrate with selected saturated salt solutions of known relative humidities. Weights were monitored daily until constant weight was reached. All slices used for a_w determination were subsequently analyzed for moisture content by the standard vacuum oven method (AOAC, 1970).

RESULTS & DISCUSSION

A MAJOR CONCERN in the development of a safe bacon product through dehydration is the possible difference in a_w between the fat and lean portions of the bacon immediately after drying. Slices dried to various degrees of moisture content were manually separated into fat and lean, and each component was analyzed for a_w within 30 min of drying. The a_w (lean) was plotted against a_w (fat), and the regression line was forced through the origin (Fig. 1). The resultant slope was not significantly different ($P = 0.01$) from 1.0, as indicated by t-test. Thus, the a_w values of the two components were considered equal under the conditions of the study.

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Since variations in the fat/lean ratio of bacon are quite large, examining the effects of fat content on a_w was of prime importance. Desorption isotherms (25°C) for freeze-dried bacon slices at 10, 50, and 60% fat content are presented in Fig. 2. Fat levels of 50 and 60% are typical in bacon, whereas levels as low as 10% are only found on end slices. Generally for the isotherms studied, at constant a_w, the quantity of water sorbed increased with decreasing fat content. Superficially this finding appears to be in contrast to that of Iglesias and Chirife (1977), who detailed the effect of fat content on the sorption data for air-dried minced beef. Using a fat-add-back method (fat and connective tissue removed from samples and then added back at desired levels after drying), they determined that the isotherms were not significantly affected by fat content. Their sorption data for the minced beef study was plotted on a fat-free, dry basis. In the present study, differences in bacon isotherms with fat in situ were still evident when data were plotted on a fat-free, dry basis (Fig. 3). However, when moisture reduction was plotted against $1 - a_w$, a fat-independent relationship was indicated (Fig. 4).

Regression analysis was performed on the data at each fat level, and compared according to Neter and Wasserman (1974). In this method a sum-of-error square (SSE) is determined by first pooling all the water activity data and then comparing the SSE to that obtained considering each fat level independently. The SSE values for both models were compared by an F-test. In all cases differences were not statistically significant and indicated that the relationship was not fat dependent. The practical consequence is that by use of this fat independent relationship it is possible to

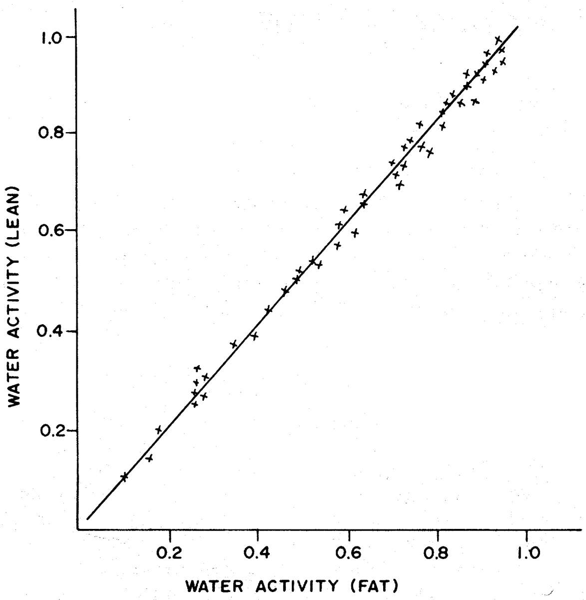

Fig. 1—Comparison of the a_w values of the fat and lean portions of bacon.

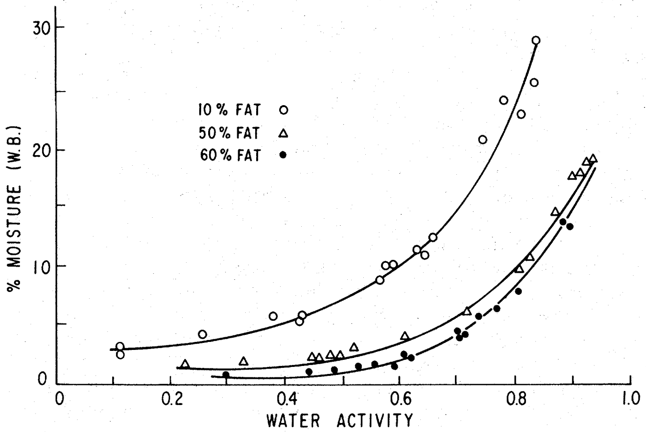

Fig. 2—Effect of fat content of bacon desorption isotherm (25°C).

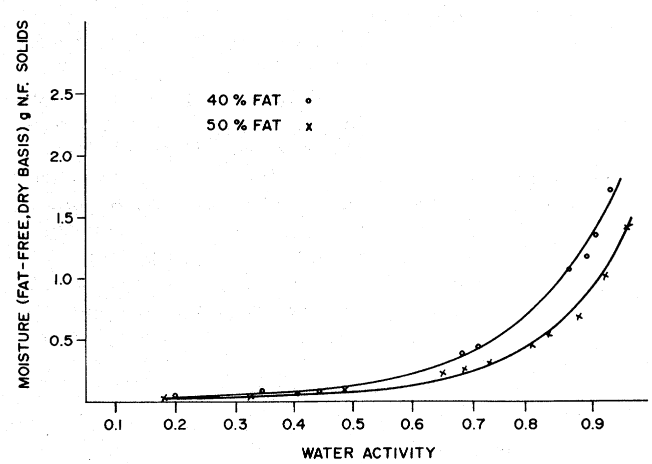

Fig. 3—Bacon desorption isotherm 25°C (fat-free, dry basis).

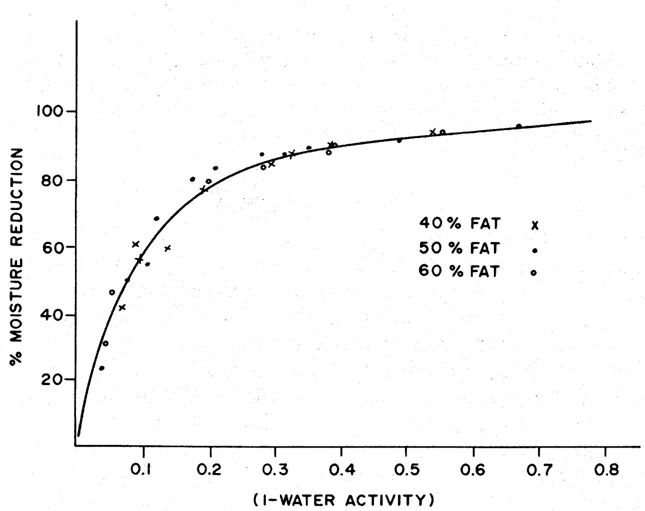

Fig. 4—Moisture reduction, water activity relationship exhibiting fat independence.

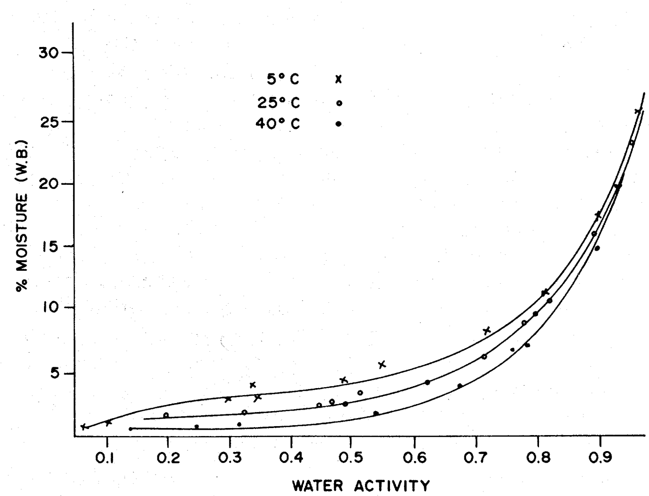

Fig. 5—Effect of storage temperature on bacon desorption isotherm (50% fat).

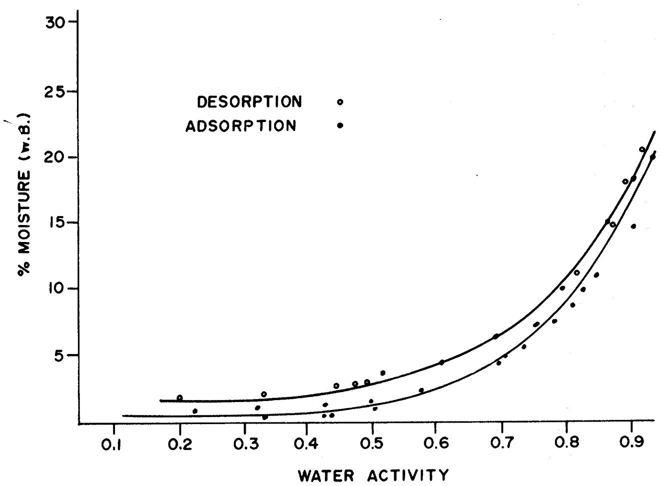

Fig. 6—Effect of sorption mode on bacon desorption isotherm (25°C, 50% fat).

predict the moisture reduction required for product stability, given only the initial moisture concentration. For example, in order to achieve an $a_w = 0.92$, approximately 60% of the water must be removed.

Desorption isotherms for freeze-dried bacon slices at different temperatures showed that, typically, the quantity of sorbed water at a given relative humidity increased as temperature decreased (Fig. 5). Temperature effects were more apparent at a_w values of less then 0.90. The stability of bacon dried to an a_w of 0.92 would not be affected by storage temperature.

The effects of sorption mode (adsorption vs desorption) are shown in Fig. 6. As with most foods, bacon slices at a iven a_w had a higher moisture content in the desorption mode. The differences in moisture content indicate the hysteresis effects and agree with the findings of Wolf et al. (1972), for freeze-dried pork. Hysteresis begins in the capillary condensation region and continues to the regions of lower a_w. Although differences in the sorption isotherms were evident, sorption mode, like storage temperature, would not affect the stability of bacon dried to an a_w of 0.92.

To determine the significance of the differences between isotherms, an effort to fit the data to known theoretical relationships was attempted. Use of the Brunauer et al. (1938), Langmuir (1918), and Harkins and Jura (1944) relationships resulted in poor correlation. Prediction was adequate only at relatively low a_w levels ($a_w \leqslant 0.6$). An empirical expression to describe the moisture-water activity relationship was then developed by the simple curvilinear regression analysis of the bacon sorption data. The equation [Eq (1)] showed an excellent fit for all bacon isotherms for $0.1 < a_w < 0.95$

$$\text{Moisture (W.B.)} = ae^{b(a_w)} \qquad (1)$$

where "a" and "b" are regression coefficients and moisture is expressed on a wet basis (g H_2O/g original wet product). Fig. 7 is typical of the agreement between experimental and predicted values. Coefficients for the isotherm equations are shown in Table 1. The isotherms were then compared by the regression comparison method shown previously. The results, when submitted to an F-test, showed that the differences in the isotherms due to changes in composition (Table 2), temperature (Table 3), and sorption mode (Table ,) were highly significant.

Multiple linear regression techniques were used to develop a relationship which included the variables a_w, moisture content, and fat content. The equations for this multiple correlation are shown in Table 5. Correlation for the isotherm

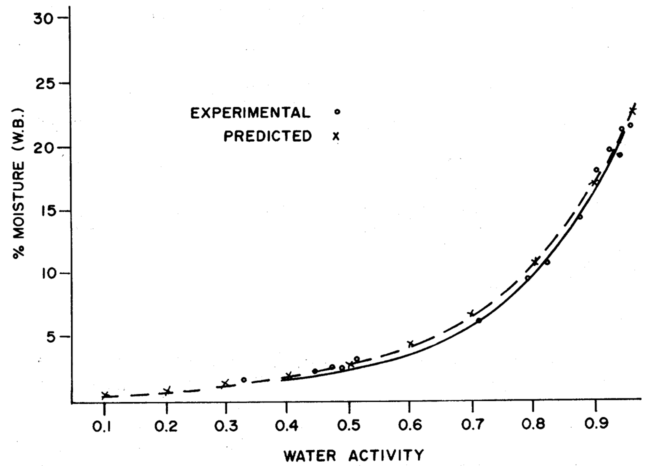

Fig. 7—Experimental vs predicted values bacon desorption isotherm (25°C, 50% fat).

Table 1—Coefficients in equations for freeze-dried bacon isotherms general form: Moisture = $ae^{b(a_w)}$

Isotherm	a	b	r
Desorption:			
5°C 30% fat	0.00760	4.5342	0.834
5°C 40% fat	0.00877	3.4532	0.999
5°C 50% fat	0.00493	3.9578	0.989
25°C 10% fat	0.01990	2.8140	0.989
25°C 40% fat	0.00199	5.2488	0.993
25°C 50% fat	0.00386	4.2252	0.987
25°C 60% fat	0.00087	5.5941	0.984
40°C 50% fat	0.00336	4.1163	0.995
40°C 60% fat	0.00349	3.6048	0.991
Adsorption:			
25°C 30% fat	0.00841	3.7003	0.954
25°C 40% fat	0.0056	3.9305	0.992
25°C 50% fat	0.0021	4.8186	0.990
25°C 60% fat	0.00189	4.7185	0.976

Table 2—Isotherm differences due to variation in fat composition

Isotherm comparisons			
Composition effects			
Temp Temp	Comparisons Comparisons	Sorption mode[a]	Fcal[b]
5°C	30% vs 50% fat	D	5.91*
5°C	40% vs 50% fat	D	6.57*
25°C	10% vs 40% fat	D	219.28**
25°C	40% vs 50% fat	D	74.50**
25°C	50% vs 60% fat	D	54.70**
40°C	50% vs 60% fat	D	48.33**
25°C	30% vs 40% fat	A	65.32**
25°C	40% vs 50% fat	A	60.23**
25°C	50% vs 60% fat	A	32.21**

[a] D = Desorption mode; A = Adsorption mode
[b] Fcal = Calculated F values
* 95% significance level
** 99% significance level

Table 3—Isotherm differences due to variation in temperature

Isotherm comparisons			
Temperature effects			
Composition	Comparisons	Sorption mode[a]	Fcal[b]
50% fat	5°C vs 25°C	D	145.23**
50% fat	25°C vs 40°C	D	19.11**

[a] D = Desorption
[b] Fcal Calculated F values
** 99% significance level

Table 4—Isotherm differences due to variation in sorption mode

Isotherm comparisons			
Sorption mode effects			
Temperature	Comparisons	Composition	Fcal[a]
25°C	Adsorption vs desorption	40%	55.92**
25°C	Adsorption vs desorption	50%	3.21*
25°C	Adsorption vs desorption	60%	30.90**

[a] Fcal Calculated F values
* 95% significance level
** 99% significance level

Table 5—Multiple regression equation for isotherm of freeze-dried bacon $Ln\ [-Ln(1-a_w)] = Co + C_1\ fat + C_2\ Ln\ moist + C_3\ fat \times Ln\ moist$

	Co	C_1	C_2	C_3	R[a]
5°C desorption	−2.531	10.381	0.437	1.101	0.867
25°C desorption	−3.133	3.990	1.171	0.909	0.958
40°C desorption	−1.641	8.456	0.314	1.106	0.880
25°C adsorption	2.415	−1.150	1.363	−1.428	0.967

[a] R = Coefficient of correlation; C = Regression coefficients

at 25°C was considerably better than that at either 5°C or 40°C.

The effects of drying method on the desorption isotherm are shown in Fig. 8. Correlation of the data for the microwave-dried product was poor due to significant melting of fat. Since adequate empirical prediction of the isotherm is a prerequisite for statistical comparison, the isotherm for the microwave-dried product was not evaluated statistically. The regression curves for the isotherms of freeze- and air-dried bacon differed significantly, indicating that additional sorption data will have to be developed for use in air drying studies. Ongoing studies in low-temperature air drying, prompted by the findings in the air-dried isotherm, indicate that sufficient water activity reduction can be accomplished in less than 2 hr with no melting of fat and no significant changes in product quality.

CONCLUSIONS

OF THE PARAMETERS investigated, composition appears to have had the most significant effect on the moisture sorption for bacon. For sufficient a_w reduction in a bacon product with unknown or widely varied fat/lean ratios, the product must be dried as indicated by the isotherm established for high fat content. An adequate prediction of fat or moisture content would permit minimal drying times to achieve safe a_w levels. The effects of storage temperature and sorption mode on the bacon isotherm are significant only for a_w values below 0.90, and would be unimportant in a processing scheme designed for a water activity reduction to 0.92. The isotherms reported here indicate that low-temperature air-drying may be a viable dehydration technique.

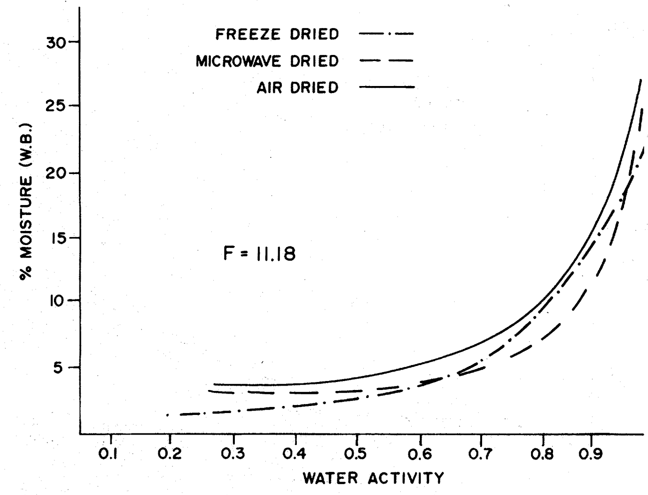

Fig. 8—Effect of drying method on bacon desorption isotherm (25°C, 50% fat).

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